Chapter 8

Digital Transmission Systems

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- Point-to-point Links
  - Link Power Budget
  - Rise-time Budget

Photonic Digital Link Analysis & Design

- Point-to-Point Link Requirement:

  - Data Rate
  - BER
  - Distance
  - Cost & Complexity

- Analysis Methods:

  - Link loss & S/N analysis (link power budget analysis and loss allocation) for a prescribed BER
  - Dispersion (rise-time) analysis (rise-time budget allocation)

Selecting the Fiber

Bit rate and distance are the major factors

Other factors to consider: attenuation and distance-bandwidth product cost of the ..connectors, splicing etc

Then decide

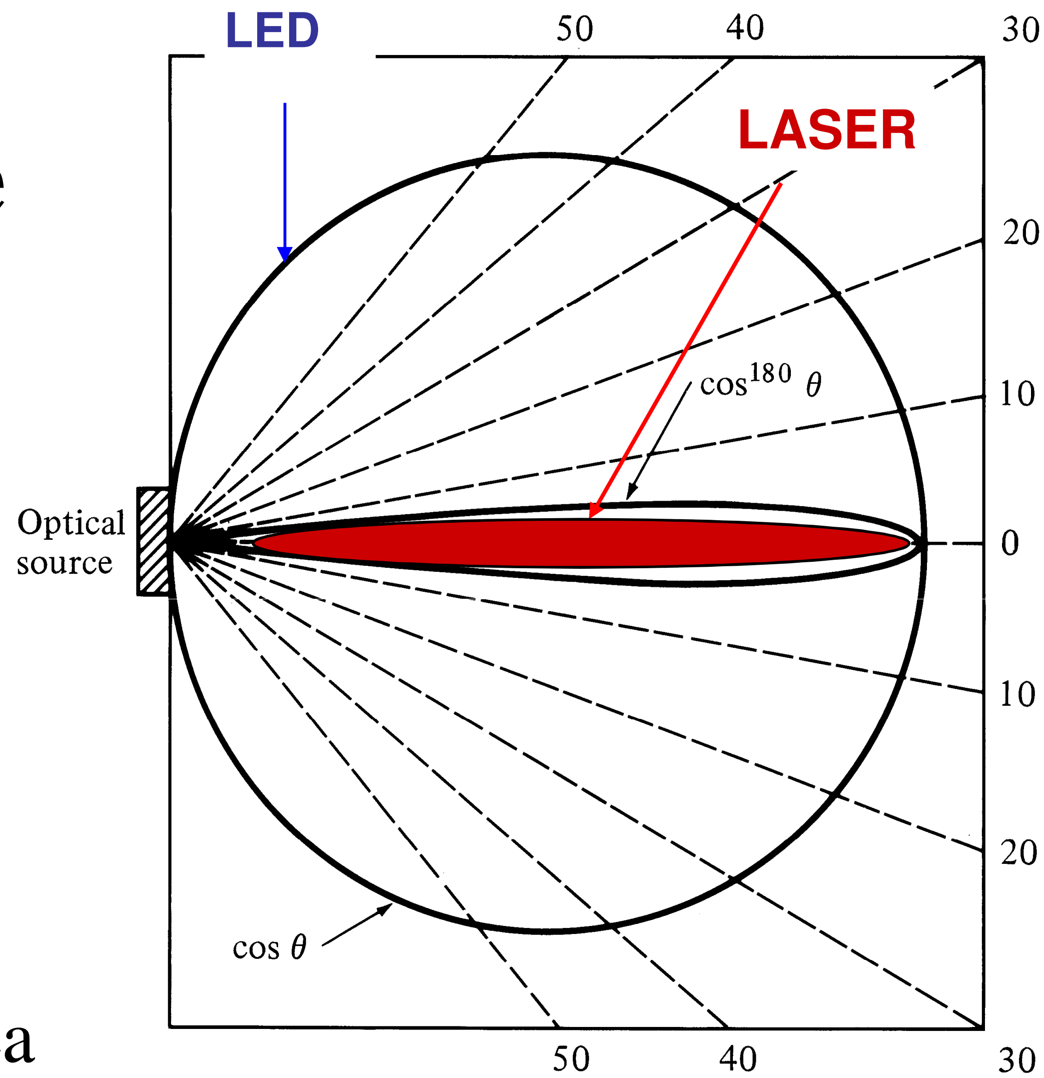
- Multimode or single mode
- Step or graded index fiber

Selecting the Optical Source

- Emission wavelength
- Spectral line width (FWHM) and number of modes
- Output power
- Stability
- Emission pattern
- Effective radiating area

Then decide

- LED
- LASER



Selecting the detector

- Type of detector
  - **APD**: High sensitivity but complex, high bias voltage (40V or more) and expensive
  - **PIN:** Simpler, thermally stable, low bias voltage (5V or less) and less expensive
- Responsivity (that depends on the avalanche gain & quantum efficiency)
- Operating wavelength and spectral selectivity
- Speed (capacitance) and photosensitive area
- Sensitivity (depends on noise and gain)

Photonic Digital Link Analysis & Design

- Point-to-Point Link Requirement:

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- Analysis Methods:

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Typical bit rates at different wavelengths

Wavelength	**LED** Systems	**LASER** Systems.
800-900 nm (Typically Multimode Fiber)	150 Mb/s.km	2500 Mb/s.km
1300 nm (Lowest dispersion)	1500 Mb/s.km	25 Gb/s.km (InGaAsP Laser)
1550 nm (Lowest Attenuation)	1200 Mb/s.km	Up to 500 Gb/s.km (Best demo)

System Design Choices: Photodetector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stablewith temperature. However PINs have lower sensitivity.
- Optical Sources:

1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

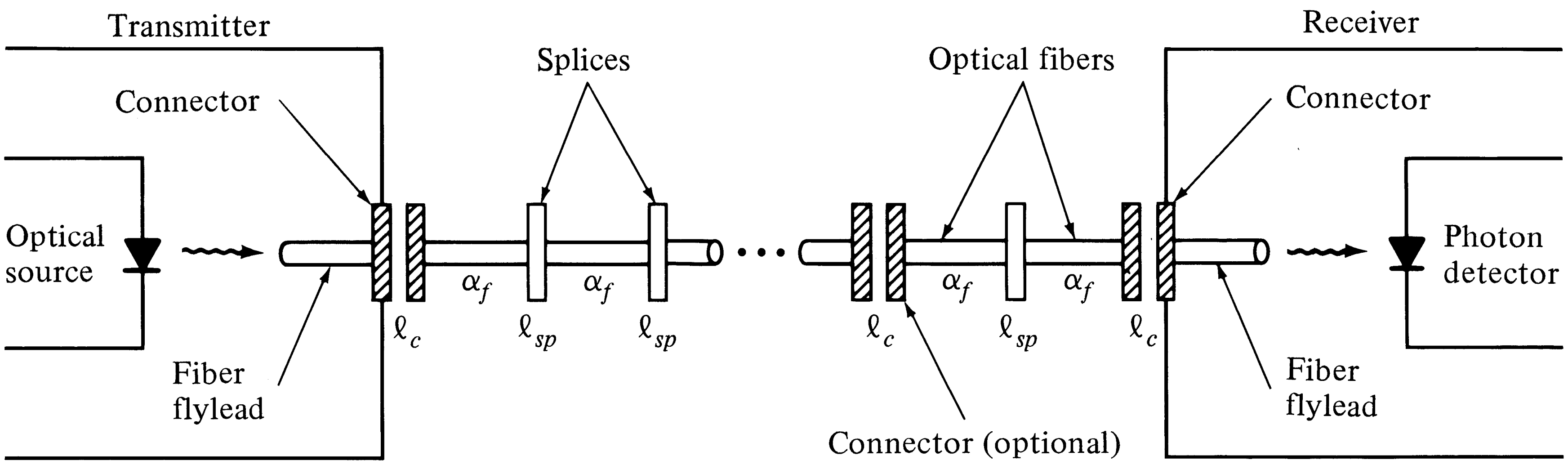
2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

Design Considerations

- Link Power Budget
  - There is enough power margin in the system to meet the given BER
- Rise Time Budget
  - Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation

Optical power-loss model



$$P_T = P_S - P_R = ml_c + nl_{sp} + \alpha L + \text{system margin}$$

P_T : Total optical power loss [dB], P_S : Output power of the transmitter [dBm],
P_R : Receiver sensitivity [dBm], l_c : connector loss [dB], l_{sp} : splice loss [dB],
α : Cable loss [dB/km], L : Cable length [km], m, n : # of connectors, splices

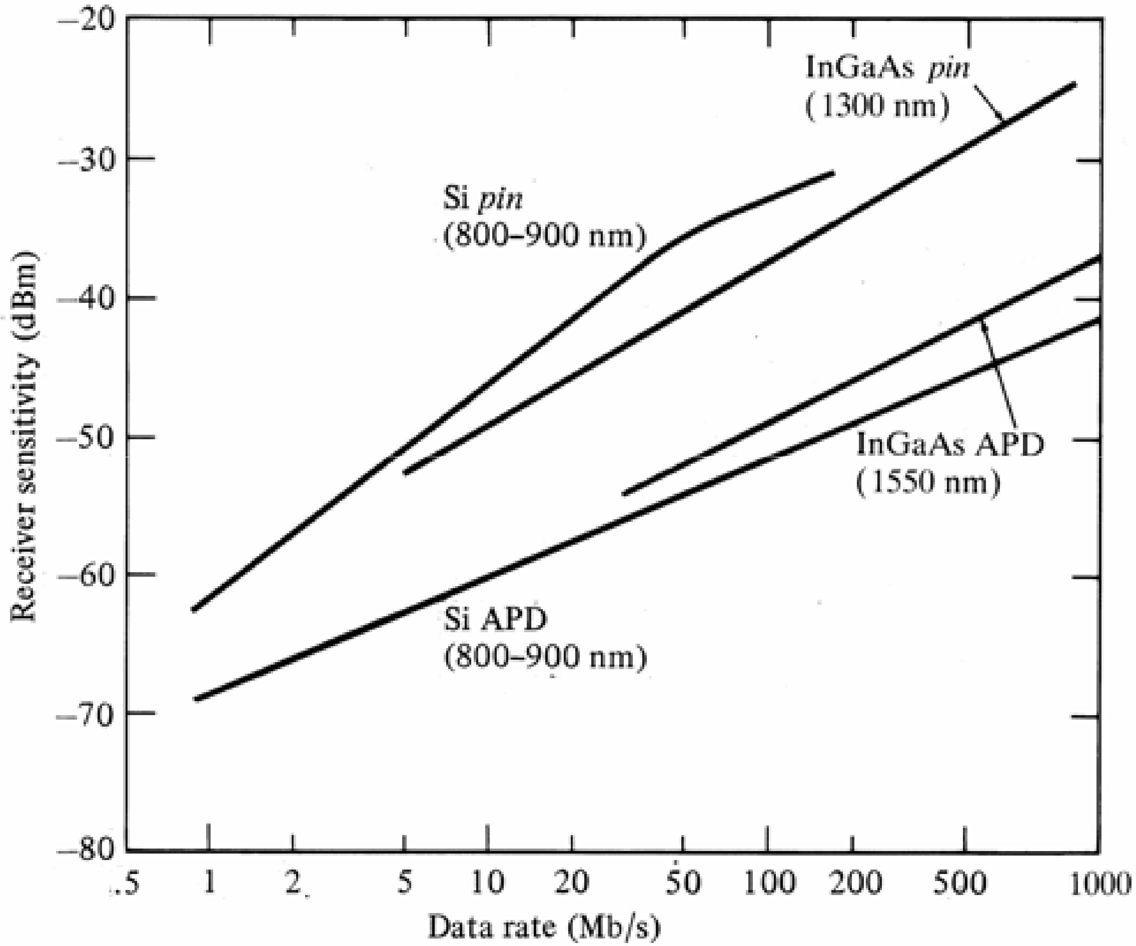
If splice loss is included in cable loss, and no connector in between ,

$$P_T = 2l_c + \alpha L + \text{system margin}$$

Example 8.1

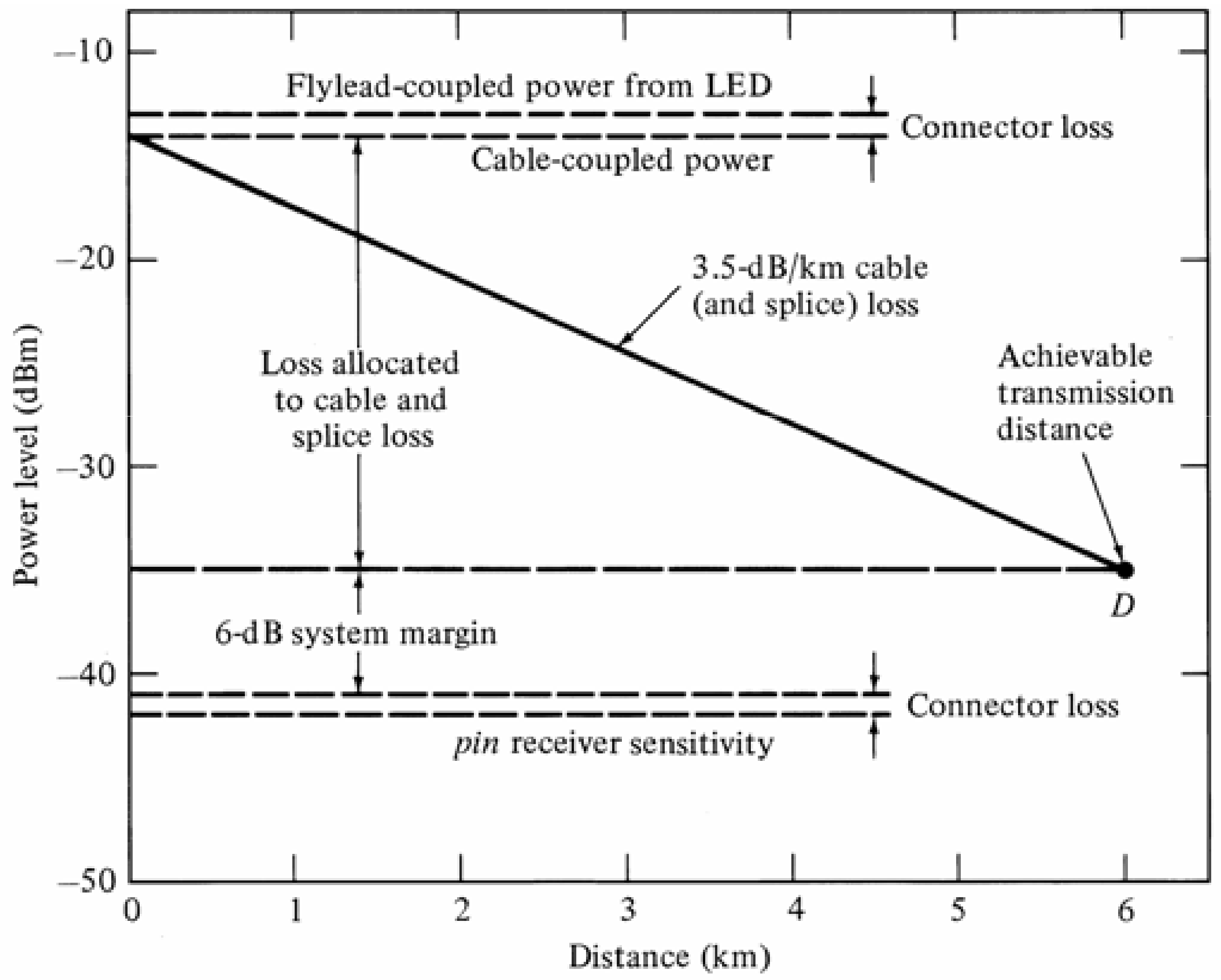
Specifications: Data Rate 20 Mb/s, BER 10^{-9},
Receiver : *pin* photodiode @ 850 nm -> Required input signal = -42 dBm
Optical source : GaAlAs LED with average optical power 50 μW = -13 dBm
Connector loss : 1 dB at both transmitter and receiver
System margin : 6 dB
Thus,
$P_T = P_S - P_R = 29$ dB = 2(1 dB) + αL + 6 dB -> $\alpha L = 21$ dB
If $\alpha = 3.5$ dB/km, then a 6-km transmission path is possible.

Receiver Sensitivities vs. Bit Rate



The Si PIN & APD and InGaAsP PIN plots for BER= 10^{-9}. The InGaAs APD plot is for BER= 10^{-11}.

Link Loss Budget [Example 8.1]



Link Power Budget Table [Example 8.2]

- Example: [SONET OC-48 (2.5 Gb/s) link]

  Transmitter: 3dBm @ 1550 nm; Receiver: InGaAs APD with -32 dBm sensitivity @ 2.5 Gb/s;

  Fiber: 60 km long with 0.3 dB/km attenuation; jumper cable loss 3 dB each, connector loss of 1 dB each.

Component/loss parameter	Output/sensitivity /loss	Power margin (dB)
Laser output	3 dBm	
APD Sensitivity @ 2.5 Gb/s	-32 dBm	
Allowed loss	3-(-32) dBm	35
Source connector loss	1 dB	34
Jumper+ Connector loss	3+1 dB	30
Cable attenuation	18 dB	12
Jumper+Connector loss	3+1 dB	8
Receiver Connector loss	1 dB	7(final margin)

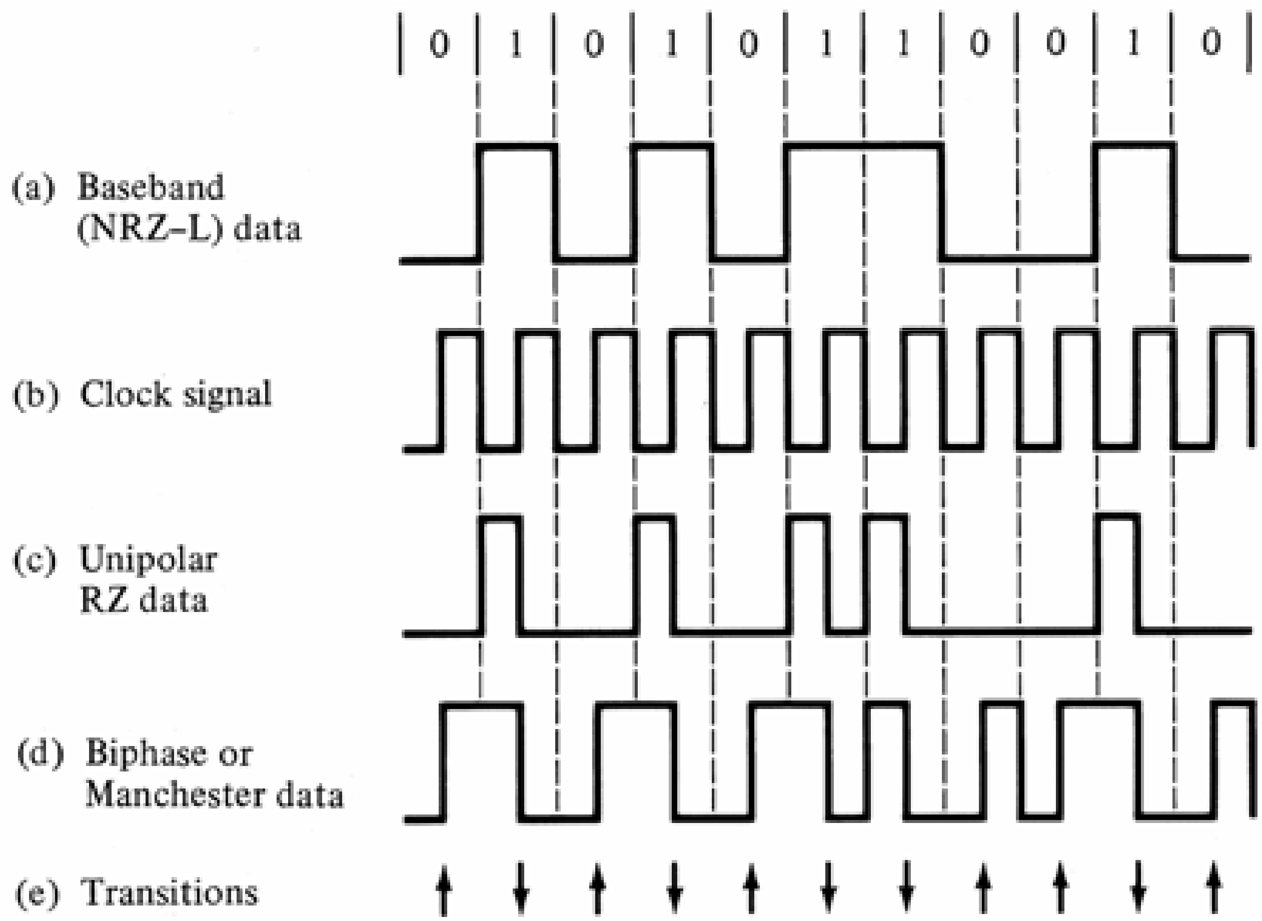
Rise Time Budget

- Total rise time depends on:
  - Transmitter rise time (t_{tx})
  - Group Velocity Dispersion (t_{GVD})
  - Modal dispersion rise time (t_{mod})
  - Receiver rise time (t_{rx})

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2}$$

Total rise time of a digital link should not exceed 70% for a NRZ bit period, and 35% of a RZ bit period

Two-level Binary Channel Codes



Rise Time

The response of the receiver front end is modeled by 1st order lowpass filter with a unit step response:

$$g(t) = [1 - \exp(-2\pi B_{rx} t)]u(t)$$

where B_{rx} denotes the 3-dB electrical bandwidth. The rise time t is defined as the time interval between $g(t) = 0.1$ and $g(t) = 0.9$, *10- to 90-percent rise time*, thus

$$t_{rx} = \frac{350}{B_{rx}}$$

where B_{rx} has unit MHz and t_{rx} has unit ns.

The rise time due to GVD over a length L is approximated by

$$t_{GVD} = |D|\sigma_{\lambda} L$$

σ_λ : half-power spectral width of the source

Modal Dispersion Rise Time

Since the bandwidth B_M can be approximated by the empirical relation:

$$B_M = \frac{B_0}{L^q}$$

where B_0 : bandwidth of a 1-km cable, q : modal equilibrium factor , range [0.5 (steady-state modal equilibrium,1 (little mode mixing)], 0.7 is reasonable.

Assume optical fiber has a Gaussian temporal response and its Fourier transform given below:

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-t^2/2\sigma^2} \xrightarrow{\mathscr{F}} G(\omega) = \frac{1}{\sqrt{2\pi}} e^{-\omega^2\sigma^2/2}$$

:The time $t_{1/2}$ required for the pulse to reach its half-maximmum value is

$$g(t_{1/2}) = 0.5\, g(0) \rightarrow t_{1/2} = (2\ln 2)^{1/2} \sigma$$

If t_{FWHM} is defined as the time when the full width of the pulse is at its half-maximum,

$$t_{\text{FWHM}} = 2t_{1/2} = 2\sigma(2\ln 2)^{1/2}$$

The 3-dB optical bandwidth is related to t_{FWHM} by

$$\omega_{3\text{dB}} = \frac{\sqrt{2\ln 2}}{\sigma}; f_{3\text{dB}} = B_{3\text{dB}} = \frac{\sqrt{2\ln 2}}{2\pi\sigma} = \frac{0.44}{t_{\text{FWHM}}}$$

Let t_{FWHM} be the rise time resulting from modal dispersion,

$$t_{\text{mod}} = t_{\text{FWHM}} = \frac{0.44}{B_{\text{M}}}$$

$$t_{\text{mod}} = \frac{0.44}{B_{\text{M}}} = \frac{0.44L^q}{B_0}$$

If t_{mod} has unit ns, and B_M has unit MHz,

$$t_{\text{mod}} = \frac{440}{B_{\text{M}}} = \frac{440L^q}{B_0}$$

Dispersion Analysis (Rise-Time Budget)

$$t_{sys} = [t_{tx}^2 + t_{\text{mod}}^2 + t_{GVD}^2 + t_{rx}^2]^{1/2}$$

$$= \left[t_{tx}{}^2 + \left(\frac{440L^q}{B_0} \right)^2 + D^2 \sigma_\lambda{}^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

Example 8.3: Rise-time budget for a multimode link

LED : rise time 15 ns; spectral width 40 nm;

Fiber : material-dispersion related rise time 21 ns over 6 km link; 400 MHz·km bandwidth-distance product, $q = 0.7$ -> t_{mod} =3.9 ns

Receiver : 25 MHz bandwidth -> t_{rx} =14 ns

$$t_{sys} = [t_{tx}^2 + t_{\text{mod}}^2 + t_{GVD}^2 + t_{rx}^2]^{1/2} = \left[15^2 + 3.9^2 + 21^2 + 14^2\right]^{1/2} = 30 \text{ ns}$$

For 20 Mb/s NRZ system, $T_{b,NRZ}$ = 50 ns. Thus, $t_{sys} < .7T_{b,NRZ}$ and the rise-time requirement is met.

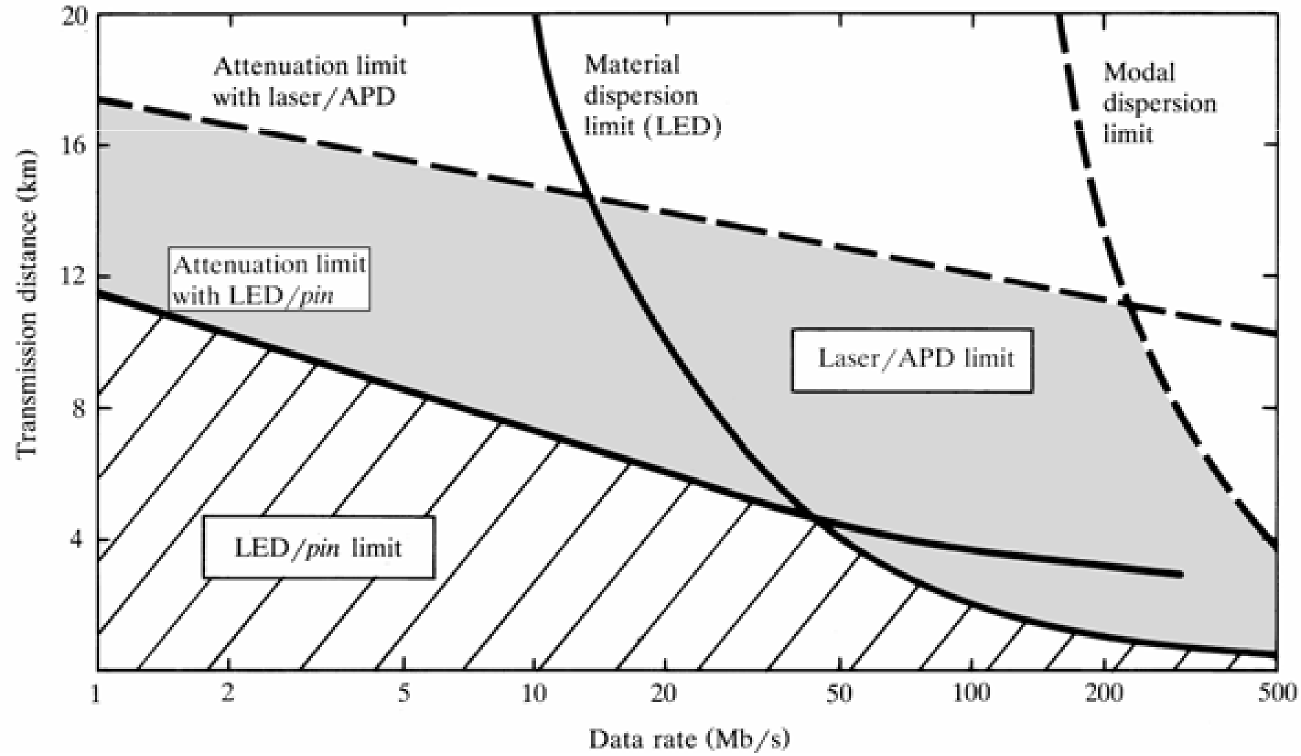
Example 8.4: Laser Tx has a rise-time of 25 ps at 1550 nm and spectral width of 0.1 nm. Length of fiber is 60 km with dispersion 2 ps/(nm.km). The InGaAs APD has a 2.5 GHz BW. The rise-time budget (required) of the system for NRZ signaling is 0.28 ns whereas the total rise-time due to components is 0.14 ns. (The system is designed for 20 Mb/s).

The total rise time is 142.7 ps

For a 2.5 Gb/s NRZ system, $T_{b,NRZ} = 400$ ps. Thus, $t_{sys} < .7T_{b,NRZ}$ and the rise-time requirement is met.

Transmission Distance for MM-Fiber in short-wavelength band

NRZ signaling, source/detector: 800-900 nm LED/pin or AlGaAs laser/APD combinations. BER=10^{-9} ; LED output=-13 dBm;fiber loss=3.5 dB/km;fiber bandwidth 800 MHz.km; *q*=0.7; 1-dB connector/coupling loss at each end; 6 dB system margin, material dispersion ins 0.07 ns/(km.nm); spectral width for LED=50 nm. Laser ar 850 nm spectral width=1 nm; laser ouput=0 dBm, Laser system margin=8 dB;



Transmission Distance for a SM Fiber Link

- Communication at 1550 nm, no modal dispersion, Source:Laser; Receiver:InGaAs-APD (11.5 log *B* -71.0 dBm) and PIN (11.5log *B*-60.5 dBm); Fiber loss =0.3 dB/km; D=2.5 ps/(km.nm): laser spectral width 1 and 3.5 nm; laser output 0 dBm,laser system margin=8 dB;